

## **Materials by Edward H. Glaessgen and Gregory A. Schoeppner**

Recent advances in the manufacturing and characterization of materials by NASA and the Air Force will lead to lighter and more durable aerospace structures.

### **Freeform fabrication**

NASA Langley Research Center has successfully developed an electron beam freeform fabrication (EBF<sup>3</sup>) process, a rapid metal deposition process that works efficiently with a variety of weldable alloys. The EBF<sup>3</sup> process can be used to build a complex, unitized part in a layer-additive fashion, although the more immediate payoff is for use as a manufacturing process for adding details to components fabricated from simplified castings and forgings or plate products. The EBF<sup>3</sup> process produces structural metallic parts with strengths comparable to that of wrought product forms and has been demonstrated on aluminum, titanium, and nickel-based alloys to date. The EBF<sup>3</sup> process introduces metal wire feedstock into a molten pool that is created and sustained using a focused electron beam in a vacuum environment. Operation in a vacuum ensures a clean process environment and eliminates the need for a consumable shield gas.

Advanced metal manufacturing methods such as EBF<sup>3</sup> are being explored for fabrication and repair of aerospace structures, offering potential for improvements in cost, weight, and performance to enhance mission success for aircraft, launch vehicles, and spacecraft. Near-term applications of the EBF<sup>3</sup> process are most likely to be implemented for cost reduction and lead time reduction through addition of details onto simplified preforms (casting or forging). This is particularly attractive for components with protruding details that would require a significantly large volume of material to be machined away from an oversized forging, offering significant reductions to the buy-to-fly ratio. Future far-term applications promise improved structural efficiency through reduced weight and improved performance by exploiting the layer-additive nature of the EBF<sup>3</sup> process to fabricate tailored unitized structures with functionally graded microstructures and compositions.

### **Advanced composites**

Delamination resistance of polymeric composite systems, particularly in the presence of peeling stresses, is low due to the low strength of polymer matrix and matrix-fiber interfaces. Subsequently, application of composites to primary structure in commercial aircraft has been very limited. Various mechanical techniques have been proposed to enhance the delamination resistance of composites, including traditional riveting, stitching and the use of small rods known as z-pins.

Z-pins improve delamination resistance at a lower weight and cost penalty than either riveting or stitching. A typical z-pin arrangement consists of pultruded rods, containing carbon fibers embedded in a polymer matrix, that are aligned perpendicular to the laminate and supported within a low-density foam preform. The pins are inserted through the prepreg using an ultrasonic hammer (discarding the foam preform). Once inserted, the pins provide direct closure tractions to the opening faces of a delamination. The z-pins are available in diameters ranging between 0.3-mm and 0.5-mm and are inserted in areal densities of between 0.5% and 4%. Experiments at NASA Langley have

shown that z-pins can enhance the effective mode I fracture toughness of composite laminates by up to 25 times the initiation value of the parent material system.

Air Force Research Laboratory (AFRL) scientists have developed a method for uniformly dispersing carbon nanofibers throughout polymeric materials. Adding carbon nanofibers into a polymeric material enhances the material's dimensional stability, abrasion resistance, electrical and thermal conductivity, and tribological properties (e.g., reduced surface friction). This method combines nanofibers with a solvent to form a solution and then introduces a polymer to the original solution to form another, nearly homogeneous mixture. Evaporation or coagulation subsequently removes the solvent from the mixture. Engineers may be able to employ the resulting polymeric nanocomposites in various forms, including conductive paints, coatings, thin films, and various structural components needed for both aerospace and non-aerospace applications.

AFRL is currently conducting follow-on research to investigate the development of a metal-coated nanotube for use in nanocomposites. This material would provide improved conductivity for applications such as signal wire shielding where reduced thickness and increased conductivity are imperative. Materials scientists may ultimately use this patented process to develop a wide variety of commercial and military applications for aerospace, electronics, automotive, and chemical markets. Some of the specific technology areas that will benefit from conductive nanocomposite materials are electromagnetic interference shielding and pulse hardening, electrical signal transfer and various electro-optical devices, such as photovoltaic cells.

### **Damage in structural materials**

Interlaminar crack growth in composite materials, often called delamination, is characterized by three modes: the Mode I opening mode, the Mode II sliding-shear mode and the Mode III tearing-shear mode. Until recently, only Mode I and Mode II were considered in damage tolerance analyses because Mode III interlaminar toughness was neither well characterized nor had it been combined with the other components to enable consideration of mixed-mode crack growth. A new test configuration, the Edge Crack Torsion test, has been developed to characterize pure Mode III delamination toughness. These tests indicate that the Mode III toughness may be significantly higher than the Mode II toughness indicating that the previously accepted practice of approximating the Mode III toughness with the Mode II value may be incorrect.

NASA Langley has recently formulated a new three-dimensional criterion for delamination growth that accounts for the Mode III component. The three-dimensional fracture criterion is a systematic extension of a two-dimensional fracture criterion that has been shown to model a range of materials well. The new criterion is assessed by plotting the predicted toughness as a function of the ratio of the three loading components. The mixed-mode criterion is readily used in conjunction with new modeling techniques that allow automated analysis of the mixed-mode strain energy release rates along a delamination front.

New computational damage science techniques are being developed at NASA Langley to understand fundamental mechanisms of damage within structural materials leading to the design of lighter, stronger and tougher materials. Molecular dynamics analysis, incorporating an interatomic potential that describes the interaction between

neighboring atoms, has been used to examine the evolution of nano-scale damage processes along grain boundaries in aluminum.

As an example, the fundamental mechanisms of deformation and crack propagation have been determined along a characteristic high-angle grain boundary wherein the atomic lattices are misoriented at about 90° relative to one another. The analysis showed that the crack growth is not symmetric along the grain boundary because of the asymmetry of the atomic lattice. The asymmetry results in a strongly preferential direction for crack growth along such grain boundaries. In one direction, the crack grows very little because much of the available energy is consumed by plastic mechanisms (e.g., deformation twinning, stacking faults, dislocations). Crack growth in the other direction is nearly brittle and proceeds through a continuous process of nano-void formation and coalescence.

Scientists from AFRL, Pratt & Whitney Aircraft, and General Electric Aircraft Engines, working under the Defense Advanced Research Projects Agency's Accelerated Insertion of Materials program, have developed a new method for characterizing the mechanical properties of aerospace alloys using micron-size test samples. The research team based the new characterization method on focused ion beam (FIB) microscopy and a commercially-available nanoindentation-based test instrument. The new method uses FIB milling to isolate and prepare single-crystal test specimens from individual grains of a conventionally processed alloy. Scientists then move the prepared specimens to a nanoindenter, which imposes uniaxial compression on the microsamples and records high-fidelity load-displacement measurements as the samples deform. With the development of this novel mechanical behavior test capability, researchers now envisage sampling the local mechanical effects of material microstructure and statistically incorporating these results in improved constitutive response surfaces, which could be used in simulations of critical component features.

This technology allows researchers to quickly access critical material information in synthetically engineered alloys. This information may lead to new breakthroughs in material development by quickly determining the suite of material properties that can be confidently produced thereby dramatically shortening system development lead times. This work is leading towards accelerated production of new designer metals that contain unique material properties (high strength, higher temperature, increased durability, etc.)

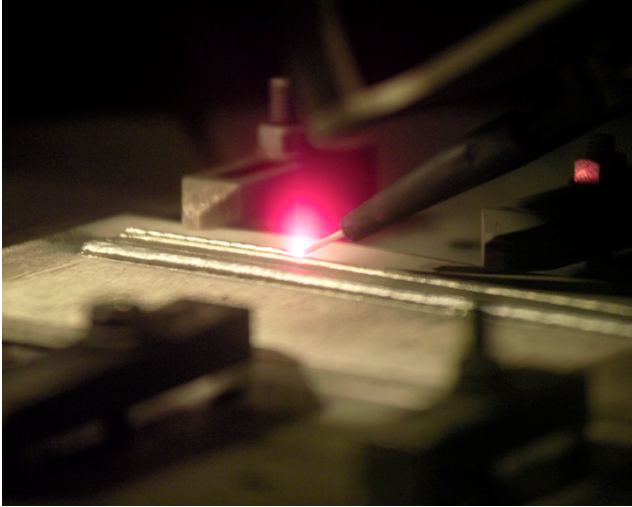


Figure 1. Photo of aluminum-lithium alloy being deposited using the EBF<sup>3</sup> process

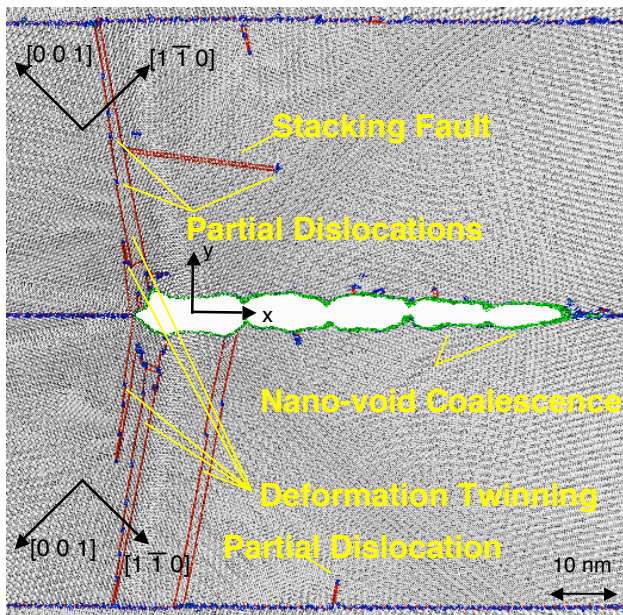


Figure 2. Mechanisms of nano-crack propagation along a grain boundary in aluminum.